UNIVERSITY OF CALIFORNIA

DEPARTMENT OF PHYSICS

LOS ANGELES 24

This Technical Report consists of reprints of papers published during the past few months by members of the staff and graduate students of the Cyclotron Laboratory at the University of California, Los Angeles

Project Designation Number NR022-053
Contract N6onr-275 Task Order IV
Under the Joint Program of the
Office of Naval Research
and the
Atomic Energy Commission

Technical Reports 17 - 20

December 1953

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December 1953

Reprinted from THE PHYSICAL REVIEW, Vol. 89, No. 6, 1163-1164, March 15, 1953
Printed in U. S. A.

Mean Excitation Potentials*

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(Received September 22, 1952)

Previous experimental results of the present authors on the energy loss of 18-Mev protons in aluminum are corrected to give a value for the mean excitation potential $I=168$ ev. It is pointed out that recent work on the range-energy relationship for protons in aluminum may indicate a variation of I with proton energy which is considerably larger than that to be attributed to the nonparticipation of the K electrons.

THE results of a measurement of the absolute energy loss of protons upon passing through various materials have been recently published.[1] Since that time, it has become evident that an out-of-date and inaccurate value of the constant e^2/mc^2 was used[2] in computing the mean excitation potentials of these materials. In the light of new work[3-5] that has been done in the field of proton ranges and excitation potentials, it was thought worth while to correct the previous computations.

In Bethe's energy loss formula,[6]

$$-dE/dx=(4\pi NZ^2e^4/mv^2)B, \quad B=Z\ln(2mv^2/I)-C_k,$$

the atomic stopping number B can be obtained from the experimentally determined $dE/d\sigma$ by using the relation

$$B=\frac{\beta^2A}{4\pi mc^2r_0^2N_0}\left(\frac{-dE}{d\sigma}\right).$$

Here $\beta=v/c$, $r_0=e^2/mc^2$, A = atomic weight of the absorber, N_0 = Avogadro's number, and $-dE/d\sigma$ is the energy loss per unit surface density of the absorbing foil. Negligible error is introduced in this experiment by using the average value of β^2 during the energy loss. Also the mean excitation potential

$$I=2\beta^2mc^2\exp[(-B+C_k)/Z].$$

It is to be noted from these relations that a half-percent error in r_0 will be reflected as a six percent error in I.

Using the value 2.818×10^{-13} cm for r_0 we obtain the corrected results for aluminum which are shown in Table I. The values of the other constants used are $mc^2=0.5108$ Mev, $N_0=6.0228\times10^{23}$ atoms per gram atom (chemical scale), $A=26.98$ g for aluminum. The weighted average for aluminum becomes $I=168$ electron volts.

TABLE I. Mean excitation potential of aluminum.

Surface density (mg/cm²)	Most probable energy loss (Mev)	Mean excitation potential (ev) (with probable error)
7.153	0.153	179.3± 21.5
14.054	0.301	181.3± 13.6
21.432	0.465	172.7± 8.6
21.532	0.470	167.0± 9.6
33.875	0.737	175.8± 7.0
38.395	0.839	173.8± 5.0
47.457	1.048	168.7± 8.3
57.493	1.276	168.6± 5.9
67.294	1.515	160.9± 5.4
76.849	1.737	161.6± 4.1

* This work was supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

[1] D. C. Sachs and J. R. Richardson, Phys. Rev. 83, 834 (1951).

[2] We are greatly indebted to Dr. Joseph E. Perry for bringing this discrepancy to our attention.

[3] N. Bloemberger and P. J. van Heerden, Phys. Rev. 83, 561 (1951).

[4] K. B. Mather and E. Segrè, Phys. Rev. 84, 191 (1951).

[5] E. L. Hubbard and K. R. MacKenzie, Phys. Rev. 85, 107 (1952).

[6] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. 9, 262 (1937). See this paper for notation.

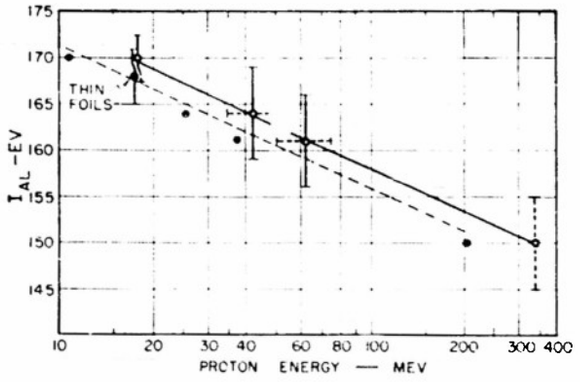

FIG. 1. Mean excitation potential of aluminum as a function of proton energy. The solid curve connects points obtained from proton range-energy experiments. The dotted curve represents an approximate thin-foil energy loss function.

Table II presents a summary of the results of recent experiments[7] which determined the mean excitation potential of aluminum. Our experiment (Sachs-Richardson) was performed with thin foils of material where the loss of proton energy in the foils was a small fraction of the incident energy (see Table I). In contrast, the remaining experimenters measured the complete proton ranges in aluminum. Assuming for the moment that there is a real variation of I with proton energy, Kaus has calculated the value of the proton energy which represents an effective value for the entire energy loss. He assumes that

$$I(E)=I_0-a\log E$$

is the functional relationship between I and the proton energy and that $a/I_0\leqslant 0.1$. From this, one obtains the result that $E_{\text{eff}}\simeq 0.6E_{\text{inc}}$. This E_{eff} for each experiment is shown in column 3 of Table II. Of course, for thin foils we have $E_{\text{eff}}\simeq E_{\text{inc}}$. In column 4 of this table, the I_{Al} values (with standard deviations) are listed. The standard deviations to the excitation potentials were obtained from the respective papers with the exception of that of Mather and Segrè. In this case the standard deviation had to be computed from their statements[8] of the approximate deviations (i.e., about 1 Mev for the energy and 0.2 g/cm² for the ranges).

Figure 1 shows a semi-log plot of the mean excitation potential of aluminum *vs* proton energy. The open circles refer to the incident proton energies (column 2 of Table II), while the solid circles represent the effective energies as defined above. The point corresponding to the thin foil result is not changed when account is taken of the effective proton energy. Upon consideration of the results in the figure, it is clear that better experimental data would be desirable before deciding that the variation of I with energy is real. It should also be pointed out that the effect of I of the nonparticipation of K electrons[6] has been taken into account in the treatment of the experimental data when use is made of C_k. Even if these calculated corrections were ignored entirely, the apparent variation of I over this energy range would only be of the order of 6 ev, which is small compared to the indicated experimental variation.

The thin foil mean ionization potentials for some other materials are shown in Table III. These results were computed using $C_k, C_l, \cdots=0$, i.e., no corrections for nonparticipating electrons were made. These corrections, if they were known, would tend to lower the values of the potentials.

TABLE II. The results of recent experiments which measured the mean excitation potential of aluminum.

Experiment	Incident proton energy (Mev)	Effective proton energy (Mev)	Mean excitation potential of aluminum (ev)
Sachs-Richardson[a]	17.8	17.8	168±3
Hubbard-MacKenzie[b]	18.0	10.8	170±2.5
Bloembergen-van Heerden[c]	35–50	21–30	164±5
Mather-Segrè[d]	50–75 340	30–45 204	161±5 150±5

[a] See reference 1.
[b] See reference 5.
[c] See reference 3.
[d] See reference 4.

TABLE III. Weighted averages of the mean excitation potentials of various materials.

Material	Weighted average mean excitation potential (ev)
Nickel	399
Copper	435
Rhodium	799
Silver	796
Cadmium	792
Tin	853
Tantalum	1148
Gold	1383
Nylon	41.3

[7] See also D. H. Simmons, Proc. Phys. Soc. (London) **A65**, 454 (1952).

[8] See reference 4, p. 193.

Reprinted from THE PHYSICAL REVIEW, Vol. 90, No. 1, 159–160, April 1, 1953
Printed in U. S. A.

Spectrometer Measurement on the High Energy Positrons of Sodium 22*

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(Received December 18, 1952)

USING a small solenoidal spectrometer,[1] a measurement of the ratio R of the partial decay constant for the lower energy spectrum A to that of the higher energy spectrum B of positrons from Na^{22} was made.

The source,[2] whose strength was approximately 0.3 millicuries, was deposited on a Nylon foil whose thickness was 2.5 mg cm^{-2}. The source was 15 mm in diameter and its average thickness 2 mg cm^{-2}.

The detector was a miniature end window Geiger counter of length 25 mm and cathode diameter 7 mm. The end of the counter formed the "energy-selecting hole" of the spectrometer. The background counting rate with no source in the spectrometer was 0.07 counts sec^{-1}. This increased to 0.09 counts sec^{-1} with the 0.3 millicurie source in position and with an aluminum plate blanking off the "angle selecting baffles" near the source. The background further increased to 0.10–0.12 counts sec^{-1} with the source in position and with a Lucite ring sufficiently thick to stop the most energetic positrons placed at the ring focus. The values quoted are for the range observed in spectrum B, points near the upper limit corresponding to the smaller background. It was by the use of such a ring absorber placed at the ring focus that a background counting rate for each of the points observed in spectrum B was determined. The most uncertain of these background rates had a standard deviation of 8 percent.

Momentum plots of the observed spectra are shown in Fig. 1. The scale of ordinates is in counts sec^{-1} per unit momentum the momentum being measured in units m_0c. The lines A and B indicate theoretical shapes for allowed spectra. Spectrum A agrees with the theoretical shape down to 0.8 m_0c, a point well below the maximum. A Kurie plot yields an end point of 540±5 kev, in agreement with prior results.[3]

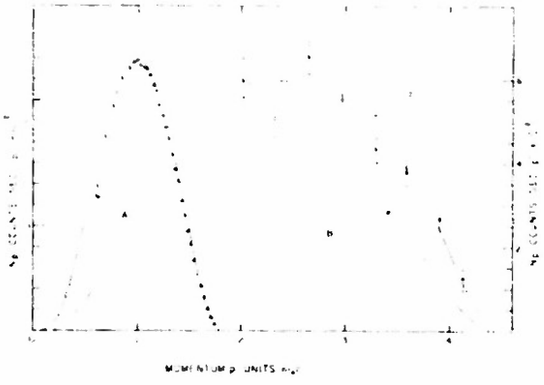

FIG. 1. Momentum plots for the two positron spectra of Na^{22}.

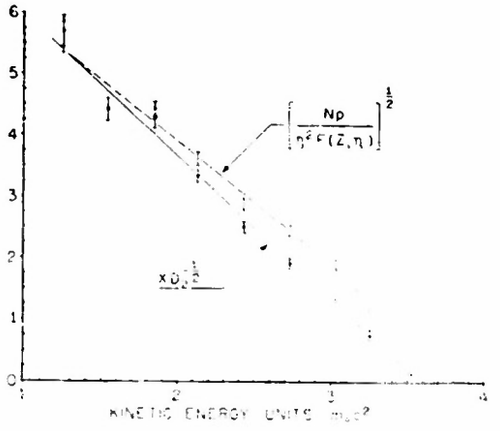

FIG. 2. Kurie plots of spectrum B.

Because of the great similarity of the transitions between the ground states of $Be^{10}-B^{10}$ and $Na^{22}-Ne^{22}$, the so-called D_2 correction[4] was considered for spectrum B. The data fit the D_2 spectrum considerably better than the allowed shape B. This is indicated by Fig. 1 and shown more clearly by the Kurie plots of spectrum B in Fig. 2. The end point of spectrum B is at 1850±60 kev, a value in agreement with the sum of the energy of the gamma-ray (1277 kev[5] of Na^{22} and the end point of spectrum A (542 kev).[3] The net counting rate for points near the peak of spectrum B was 1.5 times the background rate. The standard deviations in the net counting rates are indicated.

To obtain R we compared the areas under curves A and D_2. The result is $R=1000\pm400$. This leads, using a half-life of 2.60 years[6] for the decay via spectrum A, to a decay constant for the decay of Na^{22} to the ground state of Ne^{22} of $\geq 5.3\pm1.0\times10^{-12}$ sec^{-1}, the value being greater if a fraction of the decay of spectrum B is by orbital electron capture.

The ft value which results is $\sim10^{13}$. This is an order of magnitude less than the value based[7] on earlier experimental work[8] and about half an order less than the value based in part on a theoretical consideration.[9]

* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
[1] Byron T. Wright, Am. J. Phys. **20**, 230 (1952).
[2] Purchased from the Isotopes Division of the U. S. Atomic Energy Commission.
[3] Macklin, Lidofsky, and Wu, Phys. Rev. **78**, 318 (1950).
[4] R. E. Marshak, Phys. Rev. **75**, 513 (1949).
[5] D. F. Alburger, Phys. Rev. **76**, 435 (1949).
[6] L. J. Laslett, Phys. Rev. **76**, 858 (1949).
[7] Arnold M. Feenberg, Rev. Modern Phys. **23**, 10 (1951).
[8] K. H. Morganstern and K. P. Wolf, Phys. Rev. **76**, 1261 (1949); E. Feenberg and K. C. Hammack, Phys. Rev. **75**, 1877 (1949).

Reprinted from THE PHYSICAL REVIEW, Vol. 90, No. 2, 320, April 15, 1953
Printed in U. S. A.

The Short-Lived Radioisotopes P^{28} and Cl^{32}†

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(Received March 2, 1953)

THE series of radioactive isotopes B^8, N^{13}, Na^{20}, and Al^{24} has been reported by Alvarez[1] and by Birge.[2] These isotopes all decay by positron emission, at least some of the branches of which lead to excited states that decay by alpha-particle emission.

We have observed two new activities which result from the bombardment of silicon and sulfur by 20-Mev protons from the UCLA cyclotron. From threshold and energy considerations, we ascribe these activities to P^{28} and Cl^{32}, additional members of the above series. The method of detection involved the use of a scintillation gamma-ray spectrometer with a NaI crystal.

The half-life of the Cl^{32} activity is 0.300±0.004 second, and in addition [illegible] emits gamma radiation of energy 4.8±0.2 [illegible] P^{28} was found to be 0.280±0.030 second. It emits gamma radiation up to an energy of 7 Mev.

The thresholds for the [illegible] activities has been measured relative to the [illegible] Al^{24} at 15.4±0.5 Mev.[3] In the case of [illegible] the threshold is 15.0±0.5 Mev, and [illegible]

From [illegible] values for the masses of the P^{28} of 28.0012±0.0007 amu, and for the Cl^{32} a mass of 31.9963±0.0007 amu, using the values of Li^3 for the masses of Si^{28} and S^{32}. These nuclei are apparently just barely stable to proton emission.

We have searched for alpha-particles from these activities, using a ZnS screen and photomultiplier, but without positive results. The sensitivity of our arrangement can be indicated by the following statement: Either (a) the alpha-particles have energy less than 1 Mev or (b) the transition which results in their emission has a probability less than 10 percent of those transitions which result in gamma-ray emission.

We have also obtained some results on Al^{24} from the reaction $Mg^{24}(p,n)Al^{24}$. We observe gamma radiations of energy 7.1±0.2 Mev, 5.3±0.2 Mev, 4.3±0.2 Mev, and 2.9±0.2 Mev. Our value for the half-life is 2.10±0.04 seconds which agrees within experimental error with the value obtained by Birge.[2]

† Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
[1] L. W. Alvarez, Phys. Rev. **80**, 519 (1950).
[2] R. T. Birge, Phys. Rev. **85**, 753 (1952).
[3] C. W. Li, Phys. Rev. **88**, 1048 (1952).

Reprinted from THE PHYSICAL REVIEW, Vol. 90, No. 4, 678-682, May 15, 1953
Printed in U. S. A.

Positron-Electron Scattering at 1.3 Mev*

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(Received December 15, 1952)

Using an incident beam energy of 1.3 Mev, the ratio of electron to positron scattering on atomic electrons has been determined for the case where one-half the incident energy is transferred to the atomic electron. The measured ratio is 1.82 ± 0.11, which agrees with the theoretical ratio of 1.83, calculated from the expressions given by Møller and Bhabha when exchange effects are included. The theoretical ratio, excluding exchange effects, is 1.36.

INTRODUCTION

THE theory of electron-electron scattering, published by Møller[1] in 1932, has been checked experimentally several times in recent years[2] and appears to be correct. However, the theory of positron-electron scattering, published by Bhabha[3] in 1936, has had very little in the way of confirmation. Several experiments using cloud chambers[4] have given indecisive results because of the difficulty of obtaining enough tracks to give good statistics. Recently, using counters, Ashkin and Woodward[5] were able to measure the ratio of positron-electron to electron-electron scattering for 600-kev particles and obtained good agreement with theory. This ratio is easier to measure than the absolute cross section and is the quantity measured in this work.

The Møller formula for electron-electron scattering and the Bhabha formula for positron-electron scattering are reproduced below, where the differential cross-section is given as a function of the fractional energy ϵ imparted to the stationary particle.

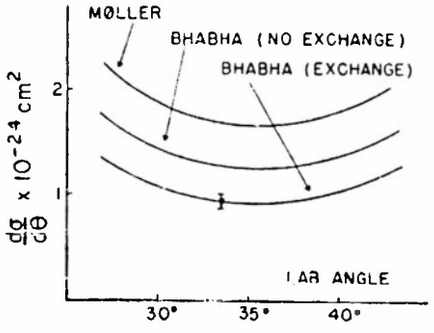

FIG. 1. Theoretical differential scattering cross section in laboratory system as a function of laboratory angle. Experimental point is shown at 33.5°.

Møller [p. 569, reference 1, with $A=\epsilon$ and $Q=mc^2(\gamma-1)\epsilon$]:

$$\left(\frac{d\sigma}{d\epsilon}\right)_M=\frac{2\pi e^4}{m^2c^4}\frac{\gamma}{(\gamma-1)^2\epsilon^2}G(\gamma,\epsilon),$$

where

$$G(\gamma,\epsilon)=\frac{\gamma}{\gamma+1}\left[1+\frac{\epsilon^2}{(1-\epsilon)^2}-\frac{\epsilon}{(1-\epsilon)}+\left(\frac{\gamma-1}{\gamma}\right)^2\left(\epsilon^2+\frac{\epsilon}{(1-\epsilon)}\right)\right].$$

Bhabha:

$$\left(\frac{d\sigma}{d\epsilon}\right)_B=\frac{2\pi e^4}{m^2c^4}\frac{\gamma}{(\gamma-1)^2\epsilon^2}F(\gamma,\epsilon),$$

where

$$F(\gamma,\epsilon)=\frac{1}{\gamma(\gamma+1)}\Big[\{1+2(\gamma-1)(1-\epsilon)+(\gamma-1)^2(1-\epsilon+\tfrac{1}{2}\epsilon^2)\}+\left(\frac{\gamma-1}{\gamma+1}\right)^2\epsilon^2\times\{3+2(\gamma-1)+(\gamma-1)^2(\tfrac{1}{2}-\epsilon+\epsilon^2)\}-\frac{\gamma-1}{\gamma+1}\epsilon\{3+4(\gamma-1)(1-\epsilon)+(\gamma-1)^2(1-\epsilon^2)\}\Big].$$

$$\gamma=\frac{1}{(1-v^2/c^2)^{\frac{1}{2}}},$$

$$F_0(\gamma,\epsilon)=\frac{1}{\gamma(\gamma+1)}[1+2(\gamma-1)(1-\epsilon)+(\gamma-1)^2(1-\epsilon+\tfrac{1}{2}\epsilon^2)].$$

The quantity $F_0(\gamma,\epsilon)$ is the first term in the expression for $F(\gamma,\epsilon)$ and refers to what Bhabha calls ordinary scattering, or the scattering that would take place if the electron and positron could not annihilate. The second term is the "exchange" term representing the possibility of annihilation and re-creation of a new pair, and the third term is the interference term between the first two. Bhabha plots $F(\gamma,\epsilon)$ and $F_0(\gamma,\epsilon)$ against ϵ for various

* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
† Now at Reed College, Portland, Oregon.
[1] C. Møller, Ann. phys. **406**, 531 (1932).
[2] L. Page, Phys. Rev. **81**, 1062 (1951); Scott, Hanson, and Lyman, Phys. Rev. **84**, 638 (1951); Groetzinger, Leder, Ribe, and Berger, Phys. Rev. **79**, 454 (1950).
[3] H. J. Bhabha, Proc. Roy. Soc. (London) **A154**, 195 (1936).
[4] Ho Zah-Wei, Compt. rend. **226**, 1083 (1948); Von O. Ritter *et al.* Z. Naturforsch. **6a**, 243 (1951); G. R. Hoke, Phys. Rev. **87**, 285 (1952).
[5] A. Ashkin and W. M. Woodward, Phys. Rev. **87**, 236 (1952).

creased to 1 mil. The new geometrical factors introduced by the wide beam caused the monitor counter to miss 16 percent of the events that were registered by the defining counter. With a 1-mil Nylon foil, multiple scattering caused another loss estimated to be around 20 percent, based on extrapolation to very thin foils of the curves given by Snyder and Scott.[6] The 16 percent figure is common to both the electron and positron cases, but since the multiple scattering is reported as 10 percent less for positrons than for electrons,[7] a correction of 2 percent was subtracted from the positron counting rate.

As can be seen from Fig. 1, the apparent ratio of electron-electron scattering to positron-electron scattering will be somewhat reduced by the above angular spread. The effect was graphically estimated to be 2 percent; hence the measured ratio was increased by 2 percent.

The positron source produced a large background of annihilation radiation. The coincidence counters were biased so that they were very insensitive to this radiation, but the main beam counter was not so biased, since it was desirable that all the incident positrons and electrons be recorded. A 12 percent correction was necessary for this gamma-background. It was determined by recording the gamma-ray background when the main beam was stopped at the entrance to the lead collimator.

In addition to the above corrections, there were several processes which could give false coincidences. The single counting rates for electrons were 20 counts per second in the defining counter and 28 in the other. Practically all of these counts were stray electrons, scattered primarily from the edges of the lead collimator. This was shown by noting that the single counting rates were not reduced more than the statistical counting error of 1.5 percent when the foil was removed. With a coincidence resolving time of 1 microsecond, the accidental rate was negligible compared with the true coincidence rate of 0.13 count per second. For positrons, the initial rates were about 40 and 59 counts per second, mostly because of annihilation quanta from the source. The order of magnitude of the total number of accidental counts was calculated from a simple integral formula involving the resolving time, the individual rates and the half-life. For the first few hours the relation was integrated numerically because of the presence of the 48- and 68-minute activities resulting from Ga^{64} and Ga^{68}. The correction was approximately 10 percent of the total recorded coincidences.

Another correction must be applied in the case where a positron stops in one counter and one of the annihilation quanta is absorbed in the other. Taking into account the number of positrons striking the counters, the solid angles seen by each counter relative to the other, and the approximate efficiency of the counters for

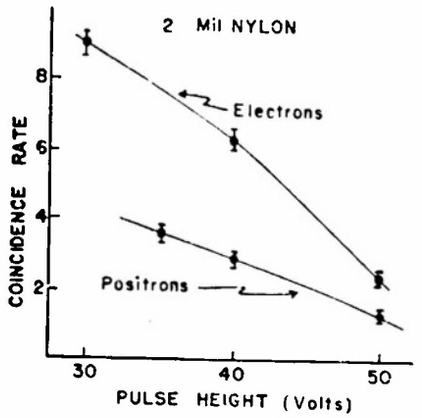

FIG. 4. Number of scattering events recorded per 10^6 incident particles on 2-mil Nylon foil as a function of discriminator bias.

0.51 gamma-rays, the correction was estimated to be around 4 percent.

Since the individual counting rates did not change (within statistical limits) when the foil was removed, it was possible to subtract false coincidences due to both the above causes by making runs with and without the foil in place. The total correction was 15 percent, which was very close to the calculated estimate.

False coincidences, which cannot be subtracted experimentally, can be recorded in the following way: When a positron is absorbed in either the defining or monitor crystal, there is a certain probability that one of the annihilation quanta will be absorbed in the same crystal. For such a gamma-ray the average path length in the crystal, for all positions of the impinging positron, is of the order of 0.4 cm. For 0.51-Mev gamma-rays in NaI, the fractional loss of photons per cm, resulting from the photoelectric effect, is 0.057.[8] For a path length of 0.4 cm, the probability of conversion is then 2.3 percent, giving a total probability of 4.6 percent, since there are two annihilation quanta. Consequently some small pulses, which would normally be rejected by the high bias setting, would have their heights increased by 0.51 Mev and be recorded, whereas the corresponding small pulses in the electron-electron scattering case would not. This effect was estimated by noting the increase in coincidence rate in the electron-electron scattering case when the discriminator bias was lowered an amount corresponding to 0.5 Mev (approximately zero bias) in one side channel at a time. The average increase for such a procedure in both channels was 47 percent. Thus the correction to be subtracted from the positron coincidence rate is 4.6 percent of 47 percent, which is 2.2 percent. There are also Compton electrons which are four times as numerous as the photoelectrons, but have an average energy of only 0.2 Mev. Lowering the bias in one channel by an amount corresponding to 0.2 Mev

[6] H. S. Snyder and W. T. Scott, Phys. Rev. 76, 220 (1949).
[7] Groetzinger, Humphrey, and Ribe, Phys. Rev. 85, 78 (1952).
[8] National Bureau of Standards Report NBS-1003 (unpublished).

increased the rate 20 percent. Hence the amount subtracted is four times 4.6 percent of 20 percent, which is 3.7 percent. When this is added to the above 2.2 percent, the total correction is about 6 percent.

RESULTS

The ratio of electron-electron to positron-electron scattering is shown in Figs. 1 and 3 after all corrections have been applied. The theoretical ratio at 33.5° is 1.83 (with exchange), and 1.36 (no exchange). The experimental ratio is 1.82 ± 0.11. Most of this error is due to uncertainties in the corrections. The Bhabha theory with exchange is thus very definitely favored.

The coincidence rates quoted above are only 0.35 times the rates expected from absolute cross section calculations. When the theoretical rate is reduced by the previously mentioned factors of 16 percent and 20 percent successively, a counting rate for electrons of 0.22 coincidence/sec is obtained. The absolute experimental coincidence rate lies somewhere between 0.27 count/sec, which is the rate just above the noise level near zero bias, and 0.13 count/sec, which is the rate at the knee of the curve. Hence no conclusions can be drawn regarding absolute cross sections.

The authors wish to express thanks to H. Keller, R. LeLevier, and R. Schrack who designed and built the spectrometer, and to G. Jones and S. Plunkett for assistance with electronic equipment.